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Research on automatic irrigation control: State of the art and recent results

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ABSTRACT

Availability of fresh water is one of the elementary conditions for life on Earth, however, water is a limited resource, which is now under an unprecedented pressure by global population growth, climate change and demand from several economic sectors such as tourism, industry, and agriculture. In particular, irrigated agriculture is one of the major water-consuming sectors. The aforementioned issues justify the need for a sustainable and rational use of water in irrigated crops, which motivates the implementation of new precise automatic irrigation technologies based on control theory. In this paper, we introduce the main concepts of control theory, how can it be applied to irrigation and a literature review of automatic irrigation control systems over the last decade. In addition, we present our latest developments in this field. In particular, we present some promising preliminary experimental results of four different control strategies applied to fruit trees in southern Spain to show the potential of the application of control techniques to irrigation.

1. Introduction

1.1. The need for better water management

Water is a scarce resource (Clothier, 2008), and its rational use is compulsory. Problems derived from lack of water will likely increase if long-term predictions on global climate change are right. Meteorological records suggest significant increases in temperature and decreases in annual precipitation, which will entail a reduction of the available water resources of the XXI century (Turral et al., 2011). Industry and tourism, among other productive activities, compete for this resource increasing its profitability and productivity. Nowadays, the economic sector that most fresh water consumes is agriculture: ca. 70% of the total resources, against the 20% used by industry and the 10% for domestic use (UN, 2009). In addition, considering the expected increase in world population (UN, 2008), it is urgent to find solutions to ensure enough food supply. This can be only achieved by increasing the world agricultural yield and water productivity, mainly from the irrigated areas as suggested by the aforementioned data.

Archaeological discoveries have identified evidence of irrigation since ancient times. A form of water management called basin irrigation began at about the same time in Egypt and Mesopotamia ca. 8000 years ago (Taylor and Ashcroft, 1972), using the water of the flooding Nile or Tigris/Euphrates rivers.

A more rational approach for optimizing irrigation is the use of automatic irrigation controllers. Automatic control has been applied in almost all engineering fields with great success; see Bennett (1996) for a brief history of automatic control, although the impact in agriculture, and in particular in precision irrigation, is limited. The key idea behind automatic control is the use of feedback. Feedback is a mechanism, process or signal that is looped back to control a system within itself. In the field of automatic irrigation, measurements of soil, plant and atmosphere variables related to the plant water status can provide the information of the consequences of previous actions to calculate the next irrigation dose.

1.2. Control theory

Control theory is an interdisciplinary subfield of science that deals with influencing the behavior of dynamical systems. In general, when one or more output variables of a system need to follow a certain reference over time, a controller acts on the inputs to the system to obtain the desired effect on the outputs.

A primitive way to implement control is the so called open-loop control (Fig. 1A), in which no measurements of the system outputs are used to modify the inputs; that is, no feedback is used. In this class of controllers, the decisions are taken a priory based on heuristics, expert knowledge or a model of the system. A particular case of open-loop is the feed-forward strategy (Fig. 1B), in which the controllers use known or estimated values of future disturbances to

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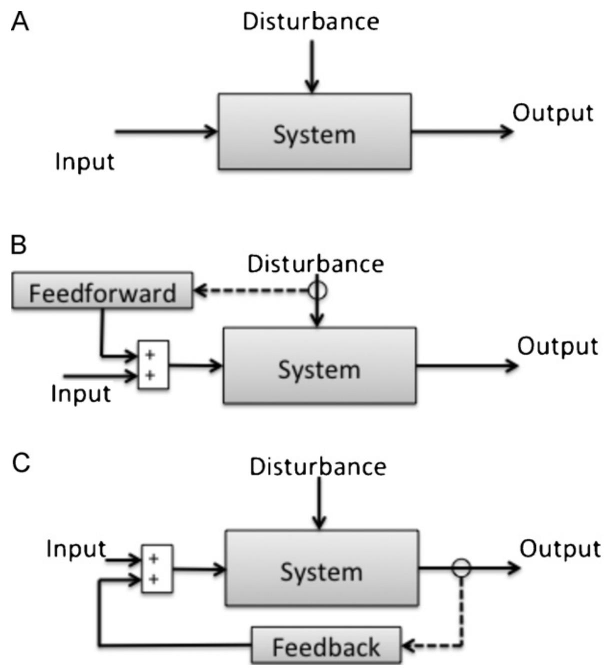

Fig. 1. The three types of control systems: (A) open loop, (B) feed-forward, and (C) feedback (closed loop).

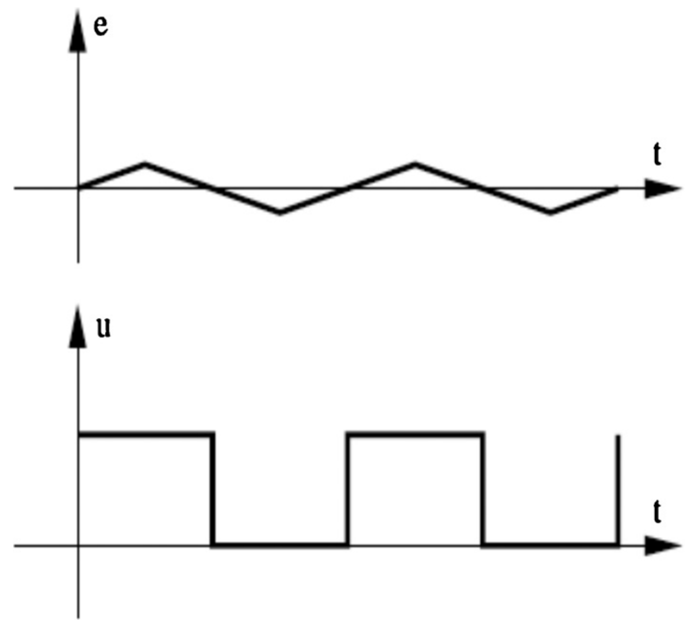

Fig. 2. Response of an on-off controller to a saw-tooth error (the control input u switches between two values based on the sign of the error e).

compensate their effects in advance. The main drawback of open-loop controllers is that they are not able to react to changes in the actual disturbances or in the system.

In closed-loop controllers (Fig. 1C), feedback is used to avoid the problems of open-loop controllers; that is, controllers use the information of the consequences of previous actions to calculate the next action. In this case, appropriate sensors are needed to close the loop. Feedback control can be said to have originated with the float valve regulators of the Hellenic and Arab worlds (Mayr, 1975), however it does not appear to have spread to medieval Europe. It seems rather to have been reinvented during the industrial revolution, where level, temperature and finally Watt's centrifugal governor where developed (Dickinson and Jenkins, 1927).

The first control strategies were based on an on-off control, consisting on switching the controller output between maximum and minimum output according to the sign of the error (Fig. 2). This is for example, the operating principle of some clepsydra (Mayr, 1975). Most on–off systems operate with a relatively large cycle time and deviation. A long cycle time gives rise to large deviations in the controlled variable, whereas a short cycle time may cause excessive wear on the relays, actuators, etc. Thus there is a trade-off between cycle time and deviation.

Modern industry has been extensively relying on automated control systems. This realization has motivated extensive research, over the last fifty years, on the development of advanced model based operation and control strategies to achieve safe, environmentally friendly and economically optimal plant operation. Classical control systems, like proportional-integral-derivative (PID) control, utilize measurements of a single output variable (e.g., temperature, pressure, level, or product species concentration) to compute the control action needed to be implemented by a control actuator so that this output variable can be regulated at a desired set-point value. In a PID controller, the control signal is generated as a weighted sum of three terms: the error between the variable and the set-point, the integral of recent errors, and the rate by which the error has been changing. The effect of changing the weight of the three terms is summarized in Table 1. This class of controllers does not need a model of the system controlled; they are only based on the information gathered by the sensors. Control systems should be evaluated for their efficiency in pursuing the target but, in general, control laws can be potentially improved by including a good model of the system, the so-called model based strategies (Pannocchia et al., 2005).

It is important to remark that automatic control is a vast discipline and an exhaustive review is beyond the scope of this paper. An introduction to process automation can be found in Love (2007), which covers a wide range of topics from instrumentation and control systems to advanced control technologies such as fuzzy logic control, artificial neural networks, genetic algorithms, model predictive control and nonlinear control, which we briefly describe next.

A fuzzy control system is a control system based on fuzzy logic, i.e. a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0 (true or false respectively). Fig. 3 shows an example of how fuzzy could interpret temperature ranges. The figure shows three different membership functions, which provide a value between 0 and 1 that measures the degree of belonging of a temperature (x axis) to a given set (cold, warm, hot). Note that these functions always sum 1, and that there are temperatures that have a nonzero membership value for more than one set. Fuzzy logic is

Table 1
Summary of PID control actions (Love, 2007).

Action	Change	Effect
P	Increase controller gain (K_C)	Increases sensitivity Reduces offset Makes response more oscillatory System becomes less stable
I	Reduce reset time (T_R)	Eliminates offset faster Increases amplitude of oscillations Settling time becomes longer Response becomes more sluggish System becomes more unstable
D	Reduce rate time (T_D)	Stabilizes system Reduces settling time Speeds up response Amplifies noise

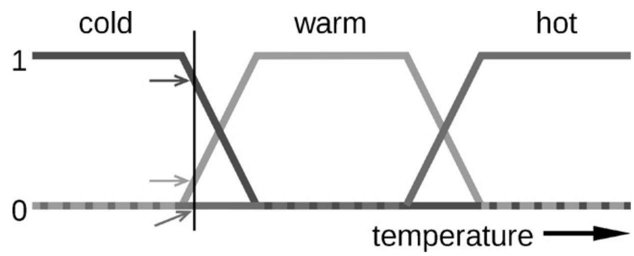

Fig. 3. Fuzzy logic interpretation of temperature ranges.

widely used in machine control. The logic involved can deal with fuzzy concepts, which cannot be expressed as "true" or "false" but rather as "partially true".

A neural network is a powerful data modeling tool that is able to capture and represent complex input/output relationships. Fig. 4 shows the elements of a multilayer neural network. Each node of the graph represents a function (usually a Gaussian function) of his inputs (the incoming arrows). The weighted output of each node may be the inputs of other nodes, often organized as layers, or the output of the neural network. Different weights provide different results. This structure allows for a very flexible representation of nonlinear functions. The weights are chosen based on a sequence of inputs and desired outputs (often denoted as training). The motivation for the development of neural network technology stemmed from the desire to develop an artificial system that could perform "intelligent" tasks similar to those performed by the human brain. The advantage of neural networks lies in their ability to represent both linear and non-linear relationships and in their ability to learn these relationships directly from the data being modeled. Traditional linear models are simply inadequate when it comes to modeling data that contains non-linear characteristics. Thus, neural networks are not really a class of controllers, but a modeling framework which can be used in advanced model based controllers.

Genetic algorithms are a class of search techniques inspired from the biological process of evolution by means of natural selection. They can be used to construct numerical optimization techniques that perform robustly on problem characterized by ill-behaved search spaces. In a genetic algorithm, a population of

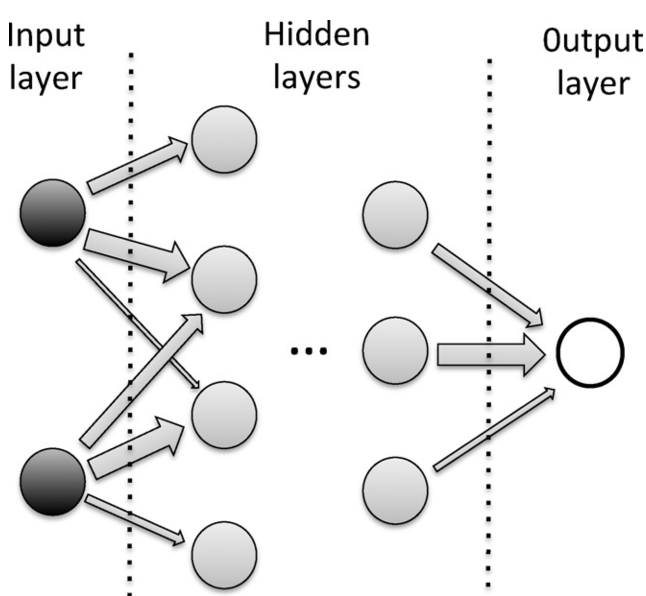

Fig. 4. Multilayer neural network with two inputs and one output. Each node represents a function, and each arrow a signal. In this figure, the width of the arrows is proportional to his weight in the function.

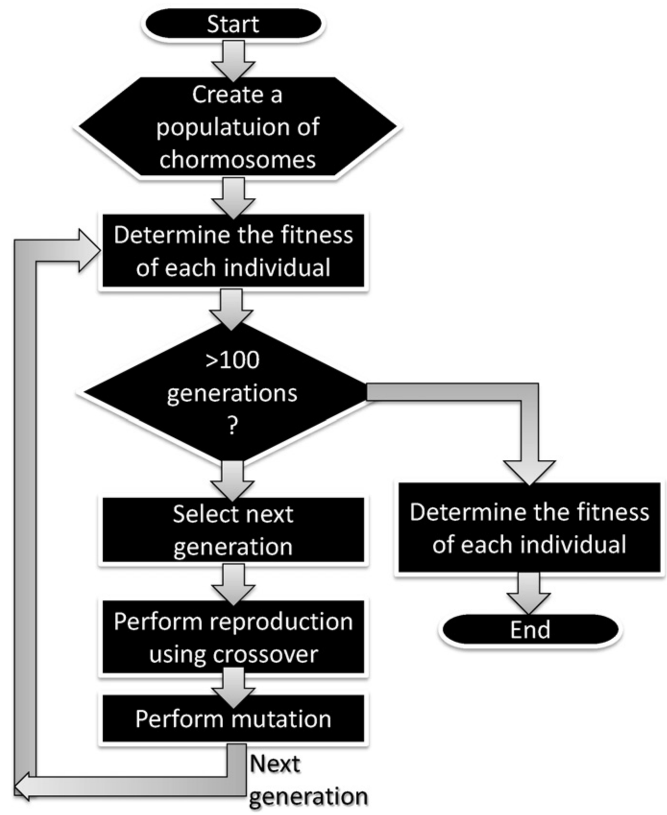

Fig. 5. Diagram of a general genetic algorithm.

strings (called chromosomes or the genotype of the genome), which encode candidate solutions (called individuals, creatures, or phenotypes) to an optimization problem, evolves toward better solutions. Fig. 5 shows a diagram of a general genetic algorithm. The solutions are denoted chromosomes. The algorithm relies on a function that provides the utility of a chromosome (*determine the fitness*) which allows one to discard at each iteration of the algorithm (*generation*) the solutions with a lower utility. With this set of solutions, a new set is obtained by mixing (*crossover*) and updating (*mutation*) the chromosomes. The algorithm stops after a given number of iterations or after a given condition is satisfied.

Model predictive control (MPC) originated in the late seventies and has developed considerably since then. This class of control strategy is based on the use of a model to predict the mathematical evolution of the system, on the minimization of a cost function based on this prediction and on the use of a receding horizon strategy (Camacho and Bordons, 2004). When the controller must take a control decision, an open-loop optimal control problem is solved based on a model of the system. From the optimal trajectory, only the first decision is applied, repeating the procedure when new measurements are available, hence, introducing feedback in order to compensate for possible disturbances and model discrepancies (Fig. 6). The various MPC algorithms differ in the class of models used to represent the system and the cost function to be minimized. There are multiple industrial applications because of the ability of MPC designs to yield high performance control systems capable of operating without expert intervention for long periods of time (Morari, 1999).

In general, there is a wide set of results in control theory for systems that can be described using linear models (both continuous and discrete time). Although there are few pure linear systems, linear approximations can be used to operate in certain conditions, however, in certain cases, these approximations do

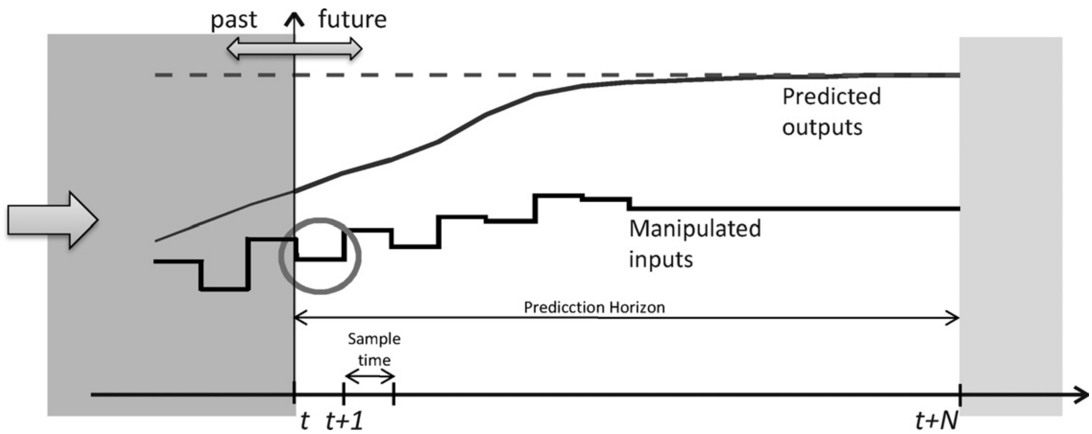

Fig. 6. Basic working principles of model predictive control: reference, predicted output and manipulated input trajectory (decision variable).

not yield appropriate results and more precise non-linear models have to be used. Nonlinear control theory (Khalil, 1992) deals with systems that are nonlinear, time-variant, or both.

After this brief review of control theory, we present next (Section 1.3) some general ideas about how to apply it for automatic irrigation purposes.

1.3. Applicability of control theory to irrigation practices

In general, automatic control has been seldom used in irrigation. The commercial solutions available on the market require the irrigation dose to be provided by the user. Only then, they are able to switch on/off the irrigation pump and to open or close the valves to apply the irrigation doses to every sector of the orchard. A popular irrigation technique to calculate the irrigation dose is based on a feed-forward strategy, which consists on applying irrigation to refill the water used by the plants the previous day, using crop potential evapotranspiration (ETc) or changes in the soil water content. This method is in fact an open-loop controller and, therefore, it presents some limitations that can be overcome by the use of feedback, mathematical models and additional information provided by plant measurements.

There are several commercial automatic controllers (Acclima, Watermark, Rain bird, Water Watcher) that regulate soil water content (SWC) based on sensor measurements, and hence operating as closed-loop controllers. These controllers apply irrigation when sensors detect that the measurements are below a certain predefined threshold until another predefined threshold is overcome (on–off control). This reference is in general established as a constant value (i.e. 80% of field capacity, or a relative ratio of the readily available water). These commercial systems have been compared by Cardenas-Lailhacar et al. (2008, 2010) concluding that, when adequate threshold are defined, all these systems have the potential to save water when compared to a traditional time-based irrigation treatment. The authors also showed that, even under dry weather conditions, the incorporation of rain sensors as a feed-forward can save substantial amounts of irrigation water.

The application of a PID strategy, as that mentioned in Section 1.2, has not yet been extensively considered in commercial controllers and could be applied not only to follow a constant reference soil water content value as abovementioned, but also to follow an optimal soil water content trajectory related to the plant water needs. In general, it can be hard to find a SWC trajectory to maximize the standard objectives (yield, water use efficiency, farm profit). Including plant variables as feedback signals could improve the performance of these controllers since these measurements involve the response of the plant to changes in soil and atmosphere. Another advantage of these variables is that they are closer to the objectives previous mentioned.

An adequate planning of any control strategy should distinguish between the choice of the control system, the choice of the targets (variables to be controlled), and the choice of the variables measured or estimated in the control system to achieve that the targets meet the objectives. In general, any measurement or estimation in the soil–plant–atmosphere system could be used as a target or as an intermediate variable in the control strategy. Main irrigation scheduling approaches are based on one or a combination of the followings: soil water measurements (soil water content or soil water potential), soil water balance calculations (using estimations of evaporation and rainfall) and plant-based measurements (tissue water status, stomatal conductance, sap flow sensors, dendrometry, etc.). A detailed comparison of all these variables is beyond the scope of this paper but an excellent review can be found in Jones (2004). The author concludes that an important advantage of plant-based measurements is their greater relevance to the plant functioning than soil-based measurements, but the practical difficulties of implementation have still limited their use by the farmers. An important effort should be tackle to reduce these difficulties.

In general, a more complete solution to the irrigation control problem should come from using a combination of all the previous ideas: feed-forward, feedback and mathematical models, considering relevant variables in every part of the soil–plant–atmosphere system (Fig. 7). In addition, advanced control laws such as the ones described in Section 1.2 could be considered for irrigation control applications.

For example, in agricultural applications, neural networks and fuzzy models have the potential to be used to model complex systems and predict future disturbances such as weather conditions or water demand. Fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans, which is in fact the case of agricultural irrigation. In addition, genetic algorithms can be applied to solve decision problems based on high complexity models of the soil–plant–atmosphere continuum.

With respect to MPC, there are few agricultural applications (mainly for regulating weather conditions in controlled environments such as greenhouses) because it is difficult to obtain precise models appropriate for control purposes; however, it is a promising methodology for the design of irrigation controllers. We will review some of these applications in the next section.

To the best of our knowledge, advanced automatic irrigation controllers have not yet been commercialized. In particular, we

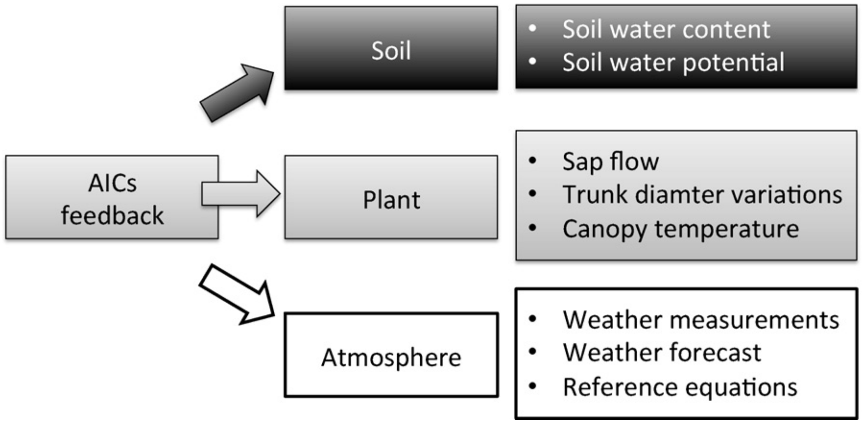

Fig. 7. Variables that can be used for automatic irrigation control.

have not found commercial automatic irrigation controllers using plant measurements as a feedback. Furthermore, the actual irrigation controllers have not still adopted more advanced control laws apart of the basic on/off threshold strategy.

In the following section, we review the main scientific contributions to this field over the last decade.

2. Research on automatic irrigation control: state of the art

Although the first papers reporting ingenious automatic irrigation devices, such as the one based on the air-lift principle hydraulic equilibrium (Chapman and Liebig, 1938) or on solenoid valves activated by custom sensors detecting soil water content deficits (Bouyoucos, 1952); date back to the middle of previous century, there has been an increasing interest of the scientific community in this problem over the last years.

We present next a review of the contributions that deal not only on how to apply a particular irrigation dose efficiently, but on how to decide the dose in order to optimize the water usage and crop objectives. The application of process control techniques to variable-rate irrigation has been recently reviewed in McCarthy et al. (2011) and we strongly recommend its reading to get a complementary view of the subject of this paper.

Most of the papers reporting automatic irrigation controllers in the last decade (Table 2) focus on regulating SWC or soil water tension (SWT) with on/off strategies based on feedback (Luthra et al., 1997; Miranda et al., 2005; Cáceres et al., 2007; Boutraa et al., 2011). These devices are relatively inexpensive and easy to use, but ground water measurements imply certain limitations: they require a large number of sensors and do not take into account the plant status and response.

In O'Shaughnessy and Evett (2010) and Peters and Evett (2008), irrigation controllers aimed at regulating canopy temperature instead of SWC were proposed. Both SWC and canopy temperatures feedback strategies were compared in Abraham et al. (2000) and Evett et al. (2000).

Xinjian (2011) and Zhu and Li (2011) have recently reported irrigation controllers which uses a combination of SWC and weather data to control drip irrigation. Xinjian's fuzzy logic controller measured air temperature, light intensity and SWC and was tested in vineyard's drip irrigation. The Zhu and Li's controller used air temperature, humidity, evaporation, rain and SWC measurements.

Table 2
A summary of the reviewed research on automatic irrigation control over the last decade.

Control strategy	Measurement	Reference	Sensor type	Crop
On/off threshold	SWC	Boutraa et al. (2011)	Not described	Wheat
		Cardenas-Lailhacar et al. (2008, 2010)	TDT, electrical resistance, electrical conductivity, impedance	Bermuda grass
		Miranda et al. (2005)	Electrical resistance (Watermark)	Bermuda grass
	SWC/LT	Abraham et al. (2000)	Electrical conductivity (Homemade)/thermistor	Okra
	SWC/CT	Evett et al. (2000)	Neutron probe/thermocouple infrared thermometers	Corn/soybean
	CT	O'Shaughnessy and Evett (2010)	Infrared thermometer	Cotton
	CT	Peters and Evett (2008)	Infrared thermometer	Soybean
	SMP	Luthra et al. (1997)	Manometer type tensiometer	–
	WD/SMP	Cáceres et al. (2007)	Modified tray method/electrotensiometer	Laurustinus
	SWC/W	Romero et al. (2009)	FDR (Enviroscan)/weather station	Almond
Modified on/off threshold	SF	Fernandez et al. (2008a,b)	Heat pulse velocity sap flow sensors (Tranzflo)	Olive
Neural network	SWC	Capraro et al. (2008)	Capacitive	Vine
Fuzzy control	SWC/AT/LI	Xinjian (2011)	STHO01/DS1802B/P9003 (datasheet references)	Vine
Expert system	SWC/W	Zhu and Li (2011)	Not described	–
	AT/AH	Zhou et al. (2009)	Not described	Jew's ear
PID	SWC	Romero (2011)	FDR (Enviroscan)	Almond
MPC	SWC	Romero (2011)	Simulated	Almond orchard model

AH: air humidity, AT: air temperature, CT: canopy temperature, FDR: frequency domain reflectometry, LI: light intensity, LT: leaf temperature, SF: sap flow, SMP: soil matric potential, SWC: soil water content, TDT: time domain transmissometry, W: weather, WD: water drainage.

They applied state space analysis methods to implement the irrigation control based on a knowledge base and an expert system rule base.

Protocols for automatic irrigation controllers have been reported based on trunk diameter variation (Goldhamer and Fereres, 2004; Garcia-Orellana et al., 2007) or sap flow measurements (Fernandez et al., 2001, 2008a). Both methods are considered having a great potential for irrigation control (Fereres et al., 2003; Jones, 2004).

The advances in wireless technology have encouraged the application of wireless sensors and/or actuators in irrigation control or monitoring experiments. Depending on distance or power requirements consideration, a wide range of communication protocols can be applied like WHF (Zhu and Li, 2011), Zigbee (Zhou et al., 2009; Xinjian, 2011) and others. In particular Zigbee protocol is becoming a popular standard for agricultural environments since it is low power consumer and therefore the communication with standalone sensors can be powered with small solar panels or even only batteries.

Recently, there has been an increasing interest on developing mathematical models representing both, the dynamics of water in the soil–plant–atmosphere (SPA) system and crop performance. Using these models is now possible to test automatic irrigation controllers in computer simulations prior to their use in field experiments. Among the most popular models are WAVE (Vanclooster et al., 1994), SPASMO (Green, 2001), SWAP (van Dam, 2000; van Dam et al., 2008), MACRO (Larsbo and Jarvis, 2003), CROPGRO (Boote et al., 1998), WOFOST (van Diepen et al., 1989) and DSSAT (Hoogenboom et al., 2004).

Model based controllers such as model predictive control (MPC) can use this knowledge to optimize irrigation, also including estimation of future changes or disturbances on the systems (e.g., weather forecast). These controllers, although successfully and extensively used in other areas of science and industry, see for example Astrom and Hagglund (2006) and Camacho and Bordons (2004), have been seldom applied in agriculture. However, we might find promising examples, especially in the management of greenhouses environmental control (Rodriguez et al., 2008; Piñon et al., 2005; El Ghoumari et al., 2005). Park et al. (2009) applied a receding horizon control scheme in a center pivot system. It demonstrated to be a viable strategy for achieving water reuse and agricultural objectives while minimizing negative impacts on environmental quality.

3. Recent results

Our group has been working over the last 4 years in developing and testing new irrigation control strategies applied to fruit orchards growing in the south-west of Spain. We present next some promising preliminary experimental results of four different control strategies to show the potential of the application of control techniques to irrigation. Further details of these experiments can be found in Romero (2011) and the specific references included in this section.

One of the most innovative and promising approaches for the automation of irrigation is based on the measurement of sap flow in conductive organs of a plant. We have developed an automatic irrigation controller based on sap flow measurements (Fernandez et al., 2008a,b,c). The system was used to daily irrigate mature olive trees using an irrigation dose estimated from sap flow measurements in the trunk of representative trees.

A proper application of this approach requires sensors that can reliably measure broad ranges of sap flow. Most of the commercially available sensors work well in rather restrictive ranges, i.e. they are not reliable in the case of very low or very high sap flows.

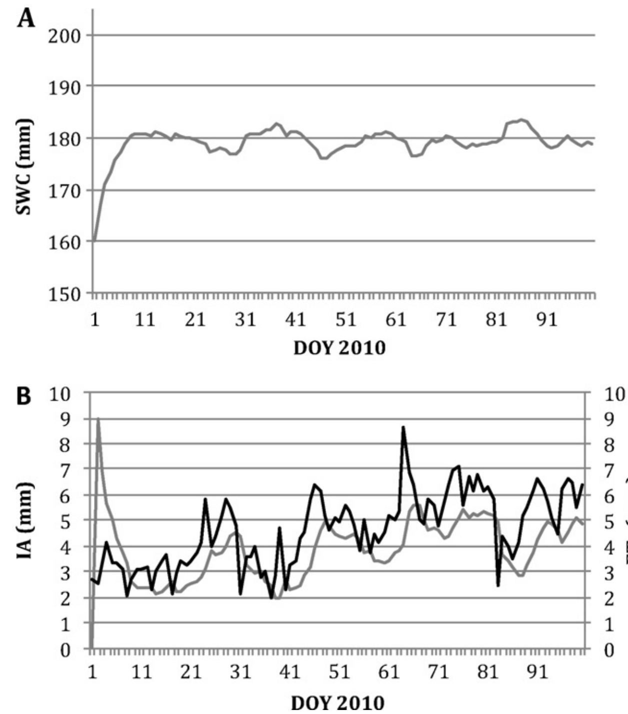

Fig. 8. Temporal evolution of (A) the soil water content (SWC, A) and (B) the irrigation amounts (IA) and potential evapotranspiration (ETo) when a PID irrigation controller is applied.

We have developed and evaluated two new methods for measuring sap flow, capable of a measurement range wider than those of most current methods, and suitable for the measurement of reverse flows (Romero et al., 2012). This is of great interest for the study of phenomena related to hydraulic lift in the root system of fruit trees.

In another line of research, our group have also implemented and tested a second irrigation controller, using a combination of feed-forward and feedback strategies based on weather and soil moisture measurements (Romero et al., 2009; Fernandez et al., 2010). This controller has been evaluated in an almond orchard, demonstrating to be useful in reducing water losses by drainage, evaporation and runoff.

Following the approach suggested in Section 1.3, we tested a PID strategy (Romero, 2011) regulating SWC (Fig. 8) on the hardware and software platform described by Romero et al. (2009) and Fernandez et al. (2010). After only 1 day, the set point was achieved and remained in ±5% set point bounds. During these periods of time, the irrigation controller operated in a fully autonomous manner, compensating weather conditions without any external information or forecast.

An alternative to the PID technique is to use the knowledge of the system's dynamics to develop model-based controllers such as model predictive control (MPC). For this purpose we developed a simplified soil–plant–atmosphere-model suitable for this technique (Romero, 2011). The model was identified and validated with field experiments in the almond orchard described by Romero et al. (2009) and Fernandez et al. (2010). This model was used not only for MPC design but also to test the performance of the controller in computer simulations (Romero, 2011).

Fig. 9A shows the trajectories of the SWC in the root zone (SWC1) and the references (set point) for the MPC and the PID simulations in the no-precipitation scenario. MPC reached the reference in the first day of simulation and remained closer to the reference for the rest of the test. From the analysis of the irrigation trajectories (Fig. 9B)

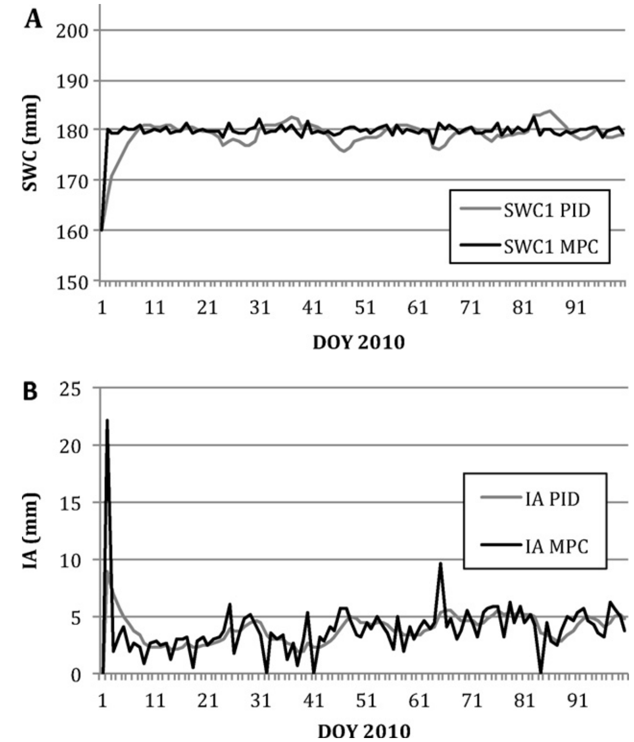

Fig. 9. Comparing soil water content trajectories (A) and irrigation amounts (B) of the MPC and PID controllers assuming no precipitations. DOY = day of year.

is also clear that the MPC change more often and react to the errors introduced by the variable weather changes (ETo).

In Fig. 10, MPC and PID are compared in the presence of precipitation events which can be predicted. Fig. 10A shows the corresponding SWC trajectories along with the daily precipitation values. In this scenario, MPC advantages are even more evident and again MPC was able to improve the control respect to the PID. Set point was achieved faster with the MPC, and SWC remained closer to the reference. The differences were especially significant in the beginning of the simulation and after the precipitation events. This was because the controller was able to adapt the irrigation needs in advance with the precipitation predictions. Note from the irrigation trajectories graph (Fig. 10B) that the MPC reduced irrigation from DOY 31, four days before the high precipitations occur (DOY 35), taking into account that there would be an excess of water inflow in the incoming days. On the contrary, PID controller reacted later, reducing irrigation from DOY 36. MPC was also able to increase irrigation (from DOY 44) three days before the PID controller did, predicting the future water inflow deficit after the precipitations period.

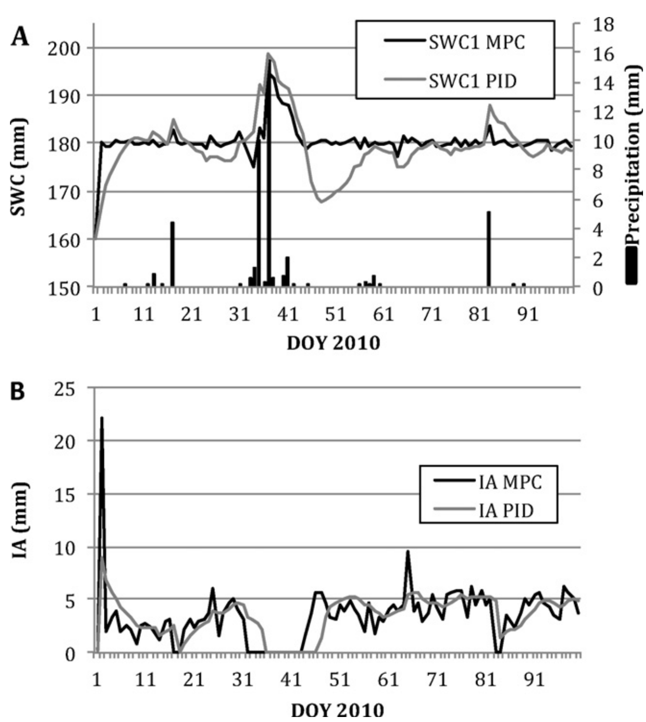

Fig. 10. Comparing soil water content trajectories (A) and irrigation amounts (B) of the MPC and PID controllers assuming precipitation events. DOY = day of year.

All these results suggest that advanced strategies could improve the localized irrigation of fruit orchards in our region. To take advantage of the SPA models that are been improved day by day, we particularly suggest more research and field test of MPC, adding weather forecast and deficit irrigation knowledge.

4. Conclusions

Optimizing water usage in irrigated crops has received a lot of attention from the scientific community. The use of advanced control techniques is a promising possibility. The results reported in the literature show that the use of these tools may have a major impact on improving the irrigation systems and the efficient use of the water resources.

Unfortunately, these results have not yet been adopted by manufactures and farmers. A greater effort must be done to demonstrate the advantages of these advances irrigation techniques (yield and water use efficiency, robustness, accuracy) in order to boost the commercialization of new products which will lead to a more sustainable and rational use of water.

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